# Lumped element resonators and

# DM Radio


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## Outline

- Field-like dark matter
- Axions (spin 0) and hidden photons (spin 1)
- Lumped-element resonators (Cabrera & Thomas)
- Hidden-photon detection
- Axion detection
- Resonant enhancement
- DM Radio science reach

# Particle-like and field-like dark matter

## Heavy Particles

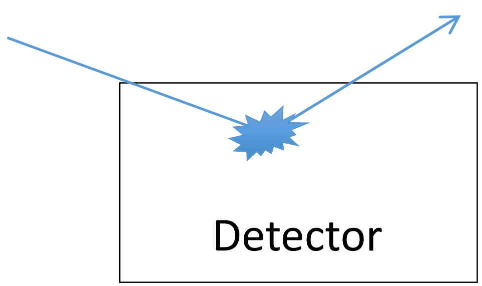
- Number density is small (small occupation)
- Tiny wavelength
- No detector-scale coherence

## Light Fields

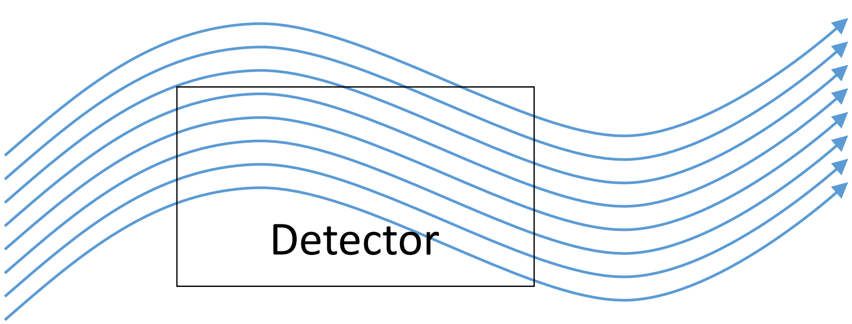
- Number density is large (must be bosons)
- Long wavelength
- Coherent within detector

$$\lambda_{\text{coherence}} \approx 100\,\text{km} \times (10^{-8}\text{eV}/m)$$

- Look for scattering of individual particles

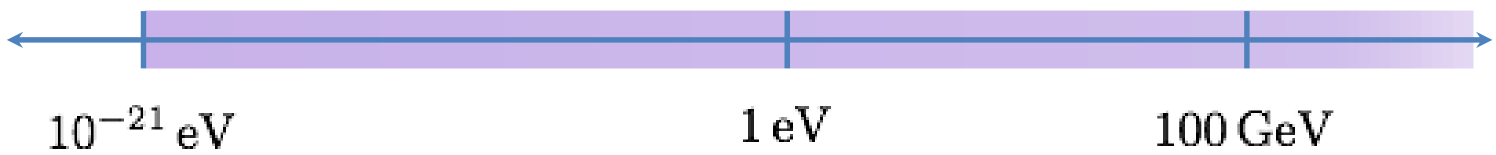



- Look for classical, oscillating background field



# The light-field dark matter zoo

DM mass:




Light (field) DM
- Spin-0 scalar
- Spin-1 vector
- Higher spin (tensor) disfavored

Heavy (particle) DM
- WIMPs
- Etc. etc.

## Light-field dark matter is a boson

1. Scalar field (spin-0)
2. Pseudoscalar (spin-0, but changes sign under parity inversion) “axion”
3. Vector (spin-1): “hidden photon”
4. Pseudovector (spin-1, but changes sign on parity inversion)

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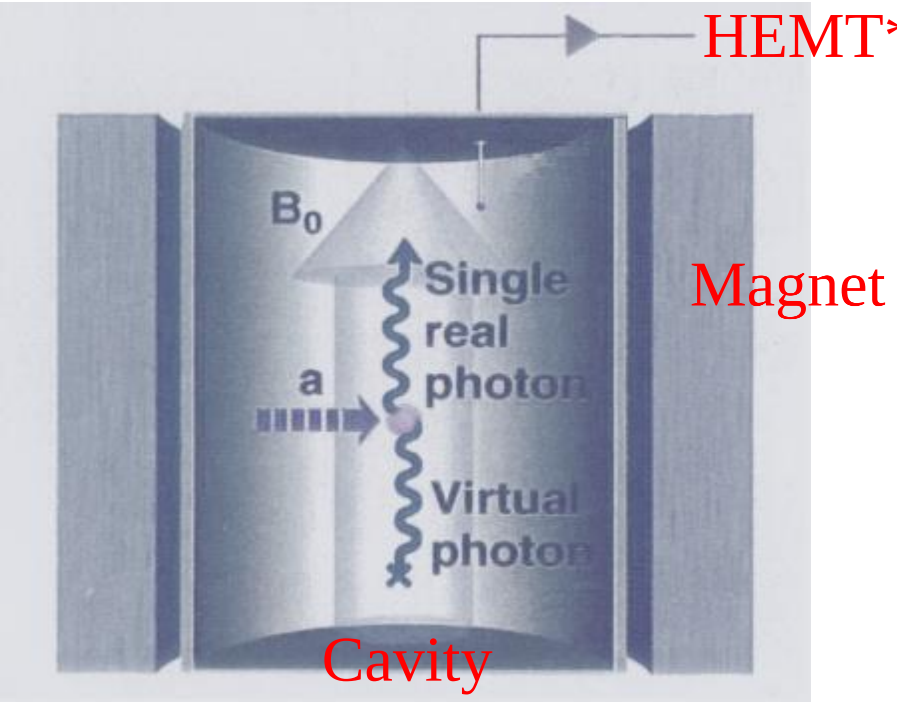
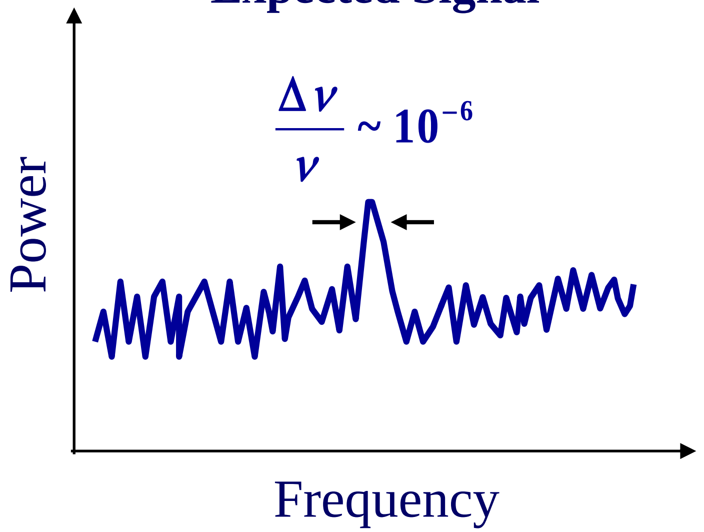
# Resonant conversion of axions into photons

Pierre Sikivie (1983)

**Primakoff Conversion**




**Expected Signal**




*High Electron Mobility Transistor

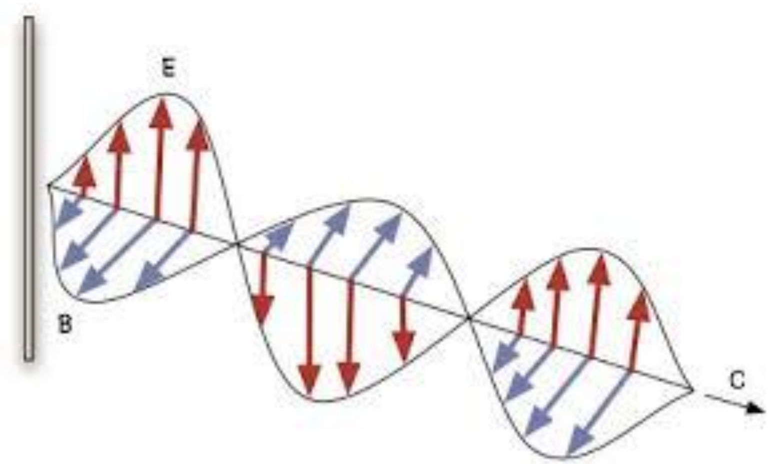
*Need to scan frequency*

Thanks to John Clarke

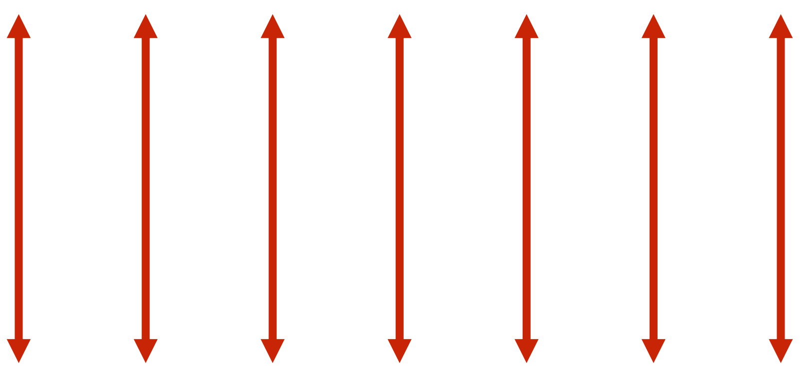
# "Hidden" photon: generic vector boson

- A new photon, but with a mass, and weak coupling
- Couples to ordinary electromagnetism via kinetic mixing

$$\mathcal{L} \sim -2\varepsilon F^{\mu\nu} F'_{\mu\nu}$$




(oscillating E' field)

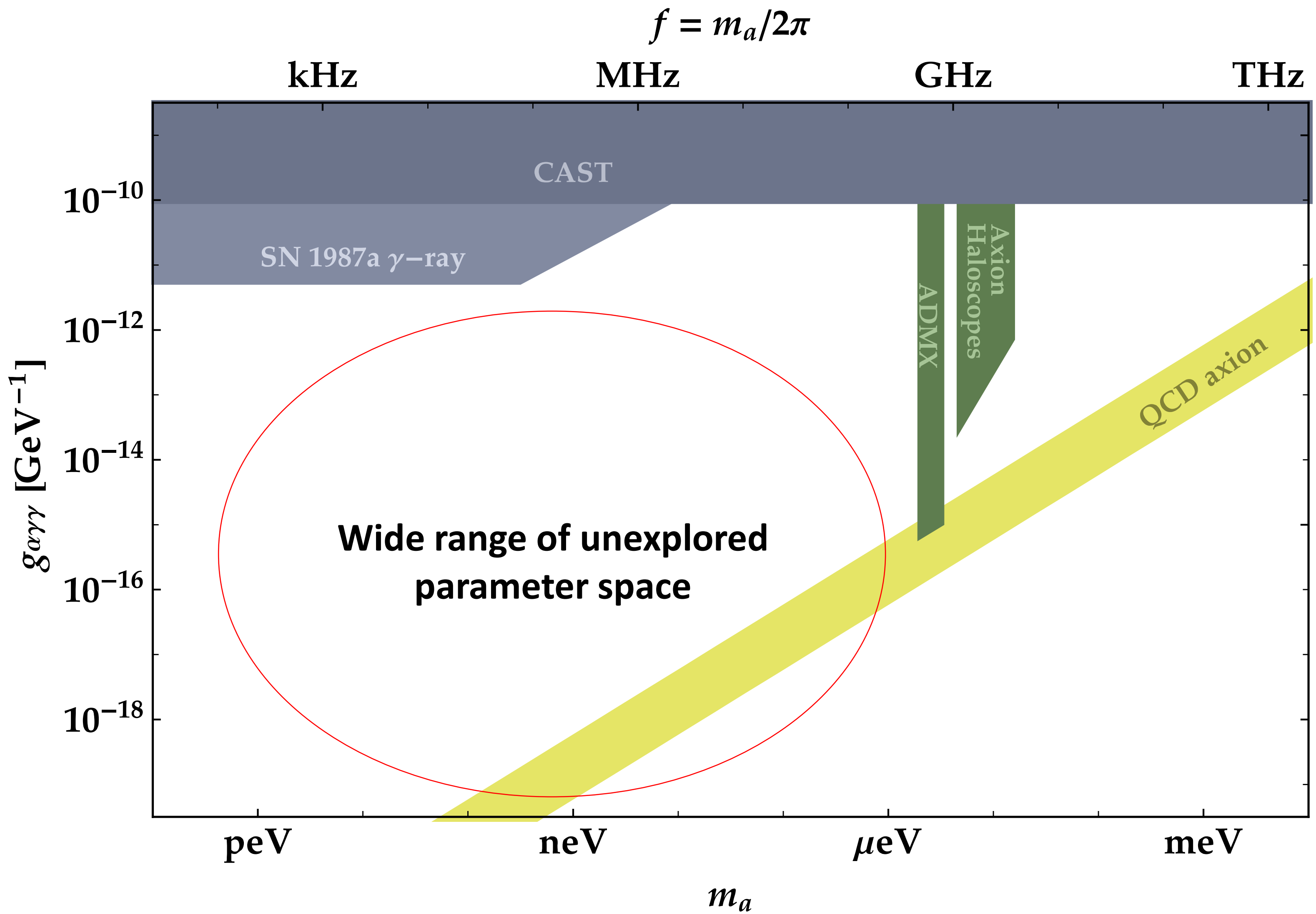


CMB photon

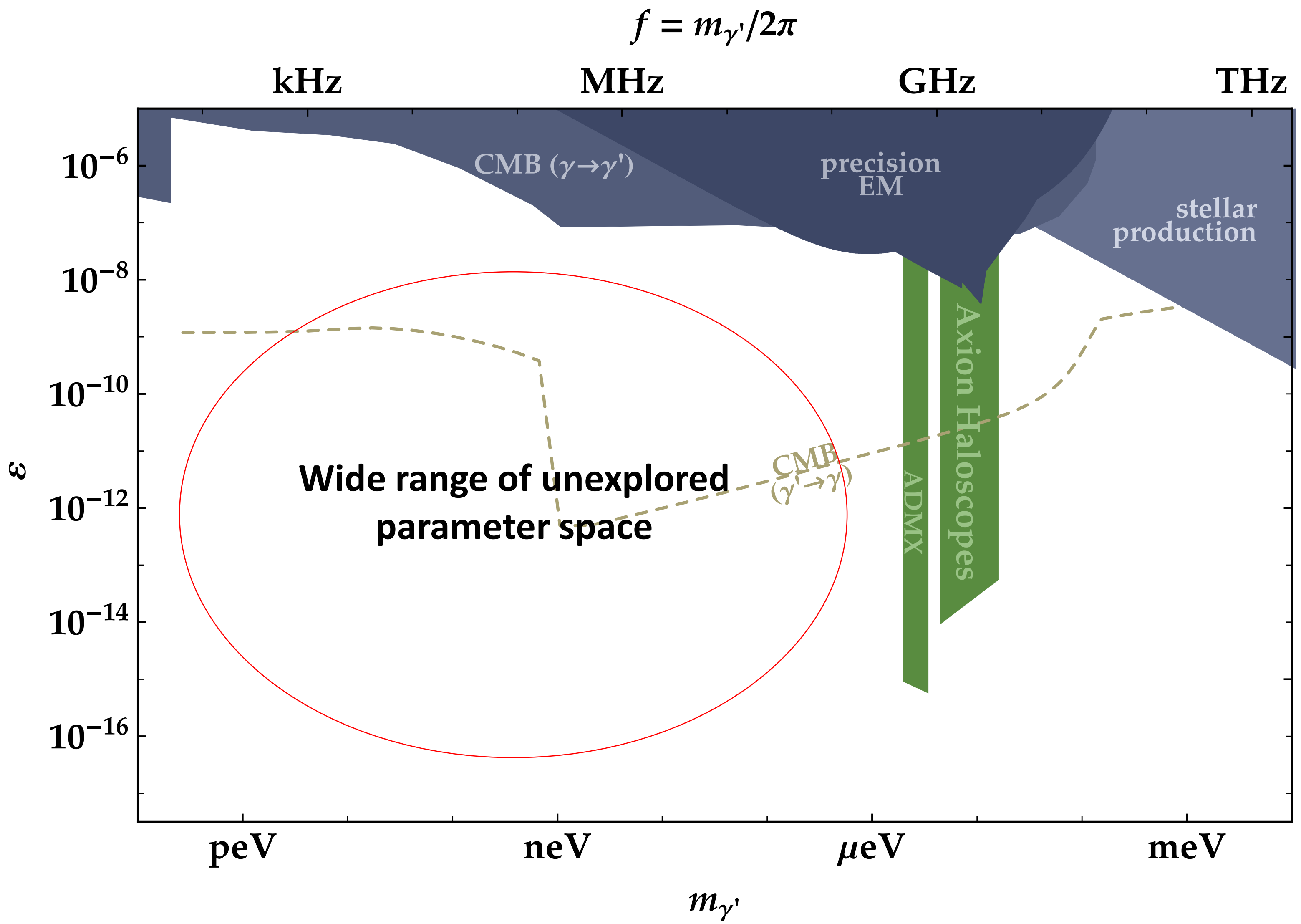
Hidden Photon DM

Hidden photon DM drives EM currents

# Axions: plenty of room at the bottom



# Hidden photons: plenty of room at the bottom



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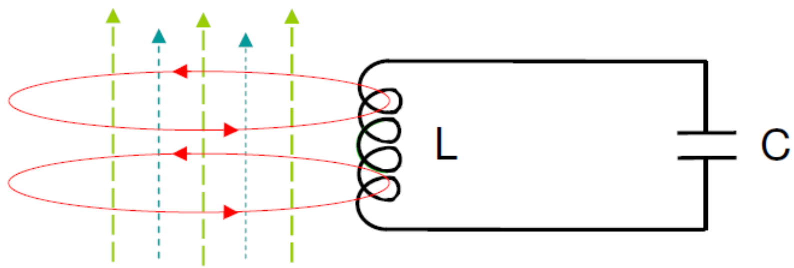
# Detecting String-Scale QCD Axion Dark Matter


Blas Cabrera
Scott Thomas

Workshop Axions 2010, U. Florida, 2010

# Dark Matter Axion Detection – Large $f_a/N$ :


- Resonant LC Circuit




$$\omega_0^2 = 1 / LC$$

$$\gamma = R/L = \omega_0/Q$$

B  j(ω)  B(ω)

Also, later: Sikivie, P., N. Sullivan, and D. B. Tanner. "*Physical review letters* 112.13 (2014): 131301.

$$\left(-\omega^2 L - i\omega R + \frac{1}{C}\right) q = \mathcal{E}$$

$$I = \frac{i\omega\mathcal{E}/L}{\omega_0^2 - \omega^2 - i\gamma\omega}$$

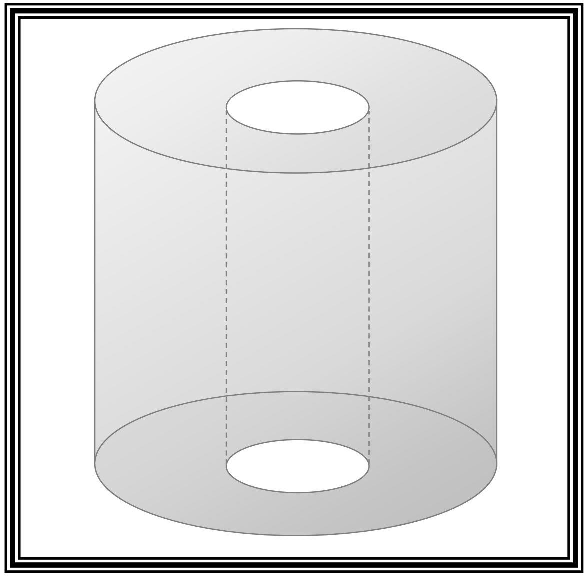
Also useful for hidden photons:
Arias et al., arxiv:1411.4986
Chaudhuri et al., arxiv: 1411.7382v2

On Resonance $$U = \frac{1}{2}L|I|^2 = \frac{1}{2}Q^2\frac{M^2}{L}|I_a|^2$$

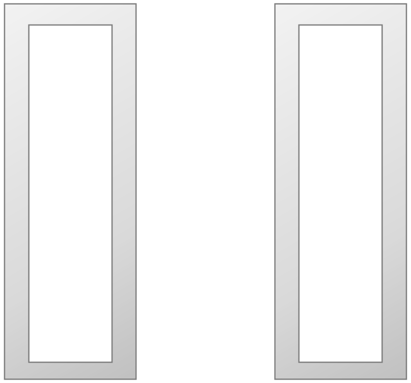
Workshop Axions 2010, U. Florida, 2010

# Block EMI background with a superconducting shield

Superconducting shield



Cross-section



- In the subwavelength limit of DM Radio, you can approximate the signal from axions and hidden photons as an effective ac current filling all space, with frequency $f = mc^2/h$
- To detect this signal, we need to block out ordinary photons with a superconducting shield

Hollow, superconducting sheath (like a hollow donut)

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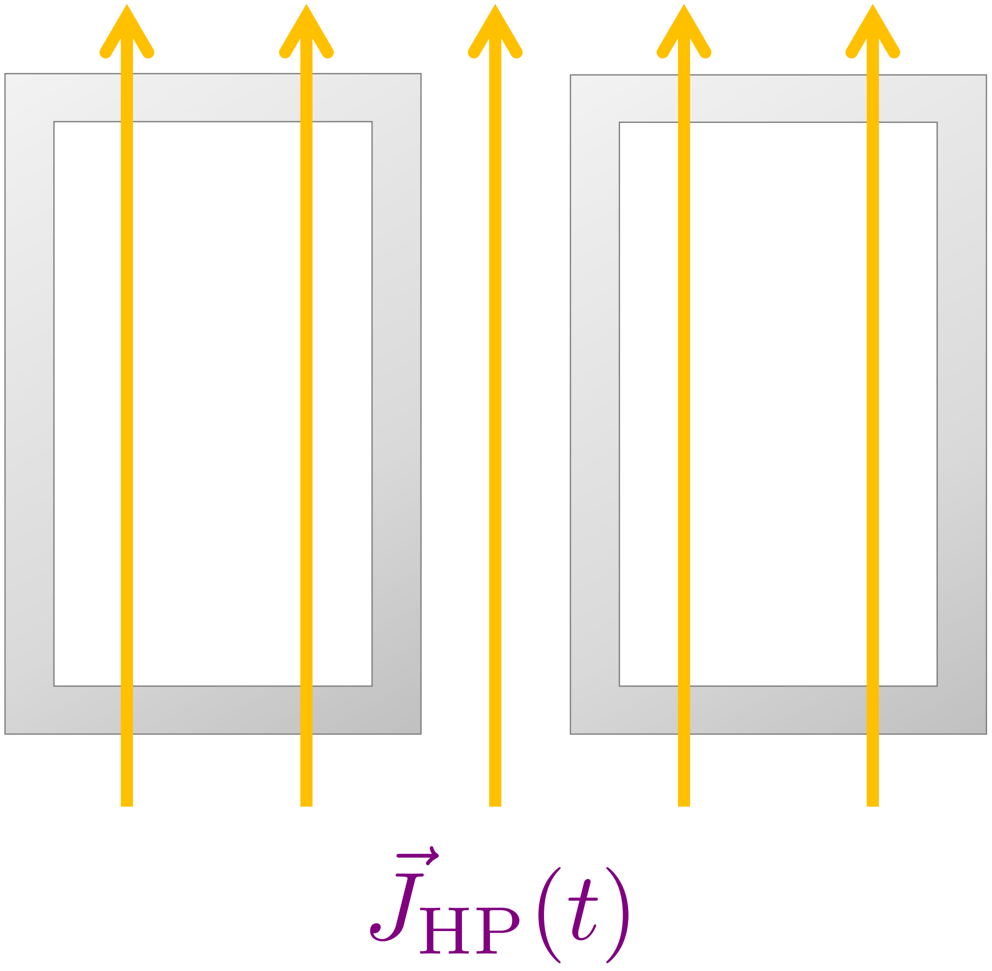
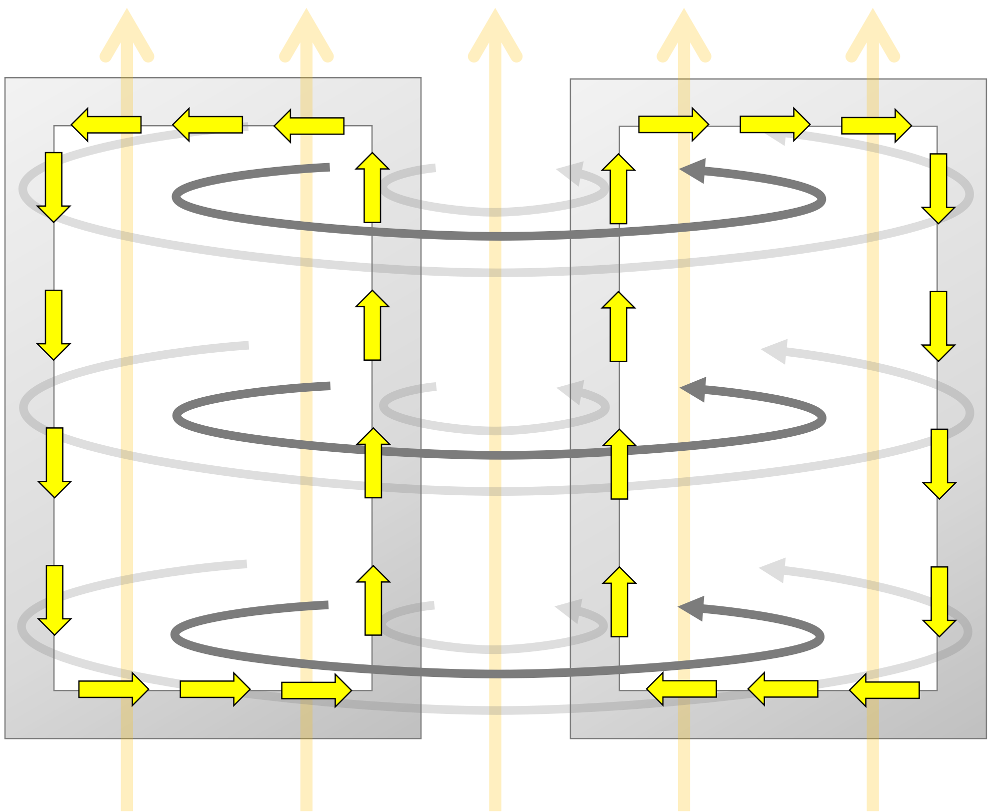
# How to measure effective hidden photon current




- Hidden photon effective ac current penetrates superconductors

# How to measure effective hidden photon current

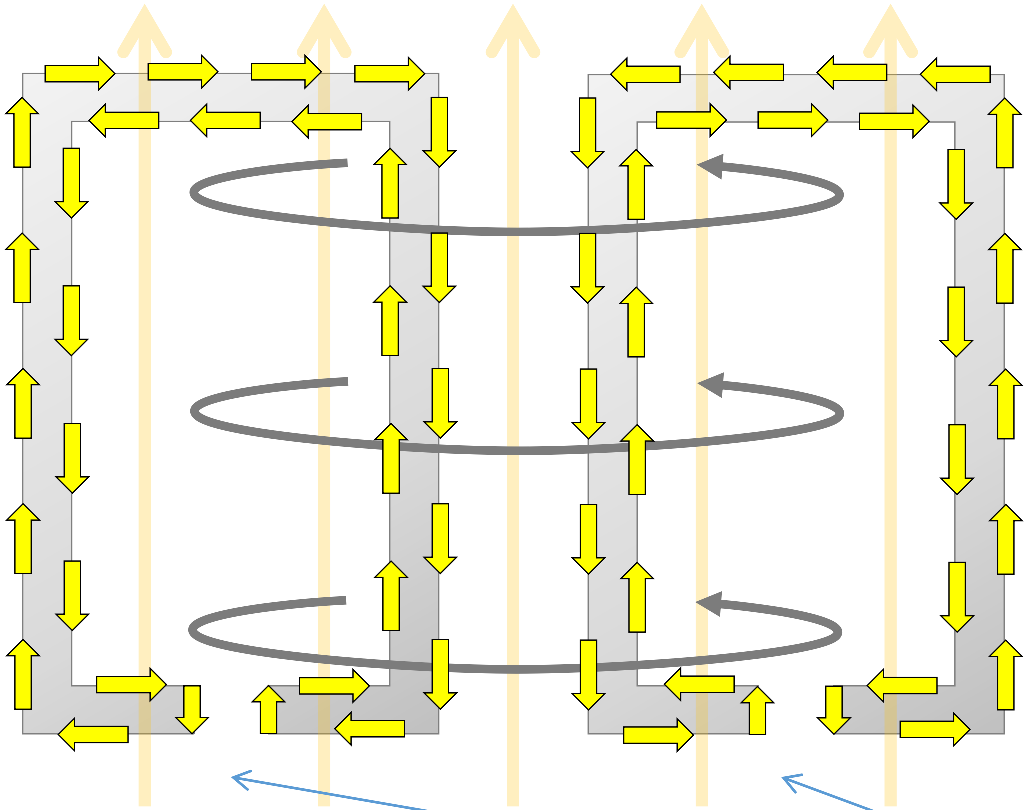


$$\vec{B}_{\mathrm{HP}}(t) = |\vec{B}_{\mathrm{HP}}(t)|\,\hat{\phi}$$

Meissner Effect

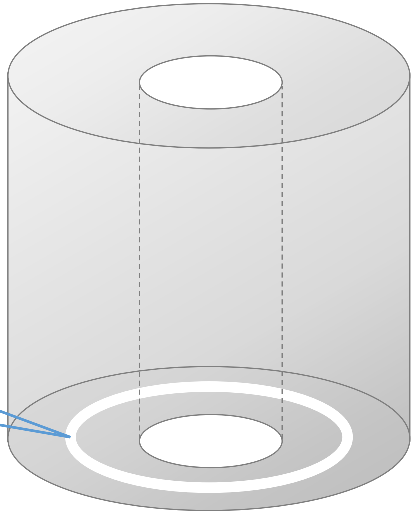
- Hidden photon effective ac current penetrates superconductors
- Generates a REAL circumferential, quasi-static B-field
- Screening currents on superconductor surface flow to cancel field in bulk

# How to measure effective hidden photon current



- Cut concentric slit at bottom of cylinder

- Screening currents return on outer surface



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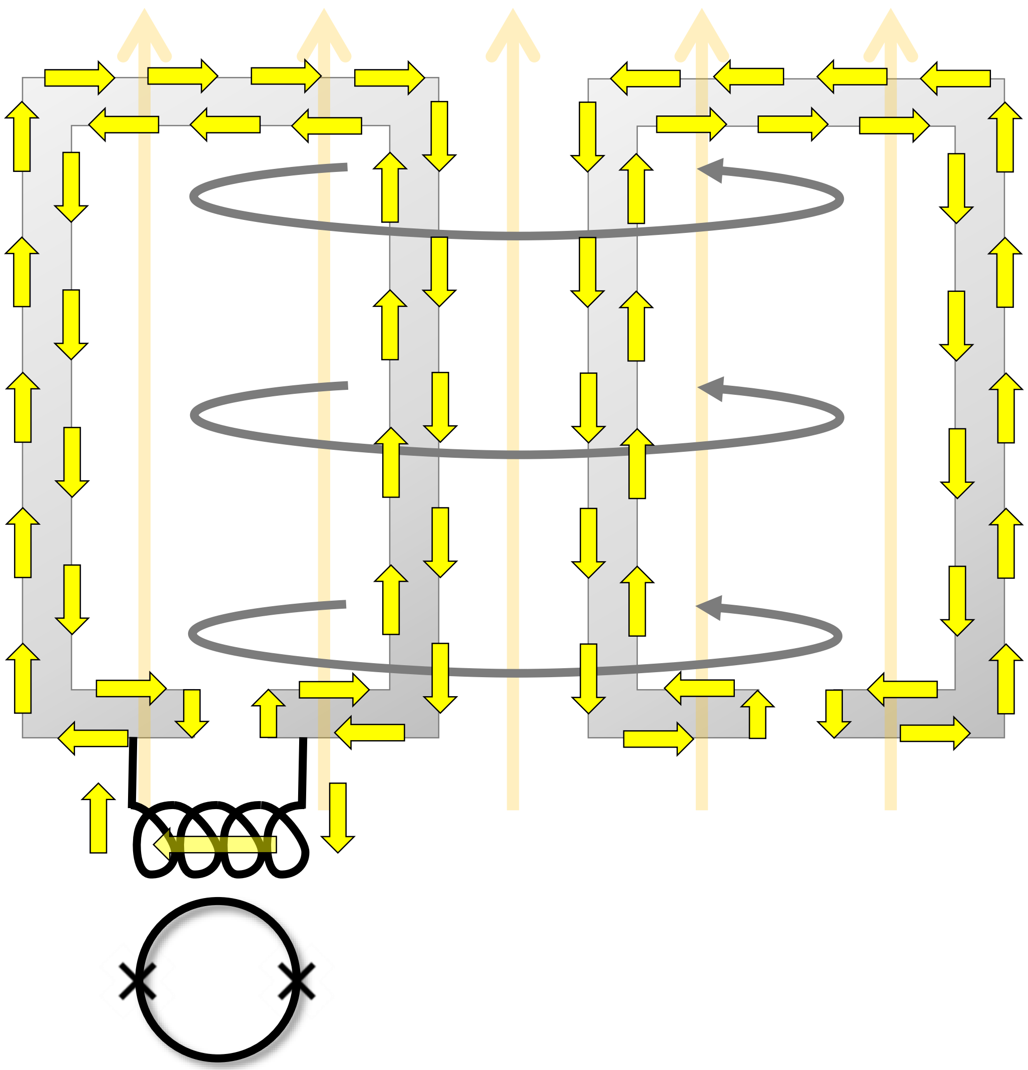

- Cut concentric slit at bottom of cylinder
- Screening currents return on outer surface
- Add an inductive loop to couple some of the screening current to SQUID

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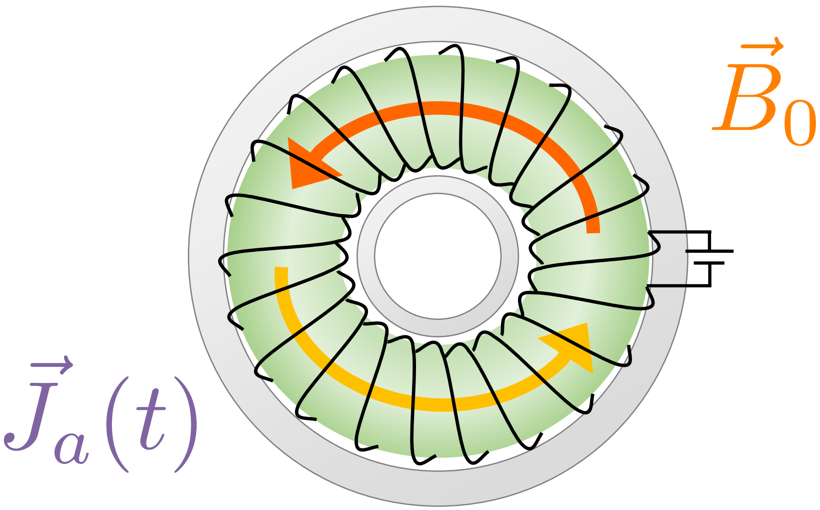
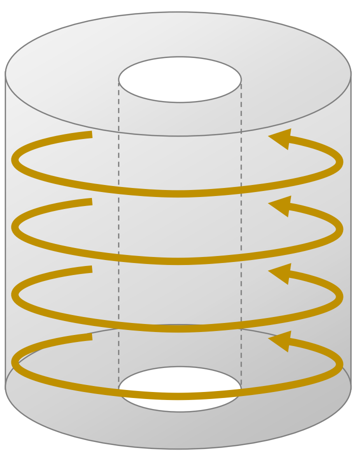
# How to measure effective axion current

Top-Down Cross-section



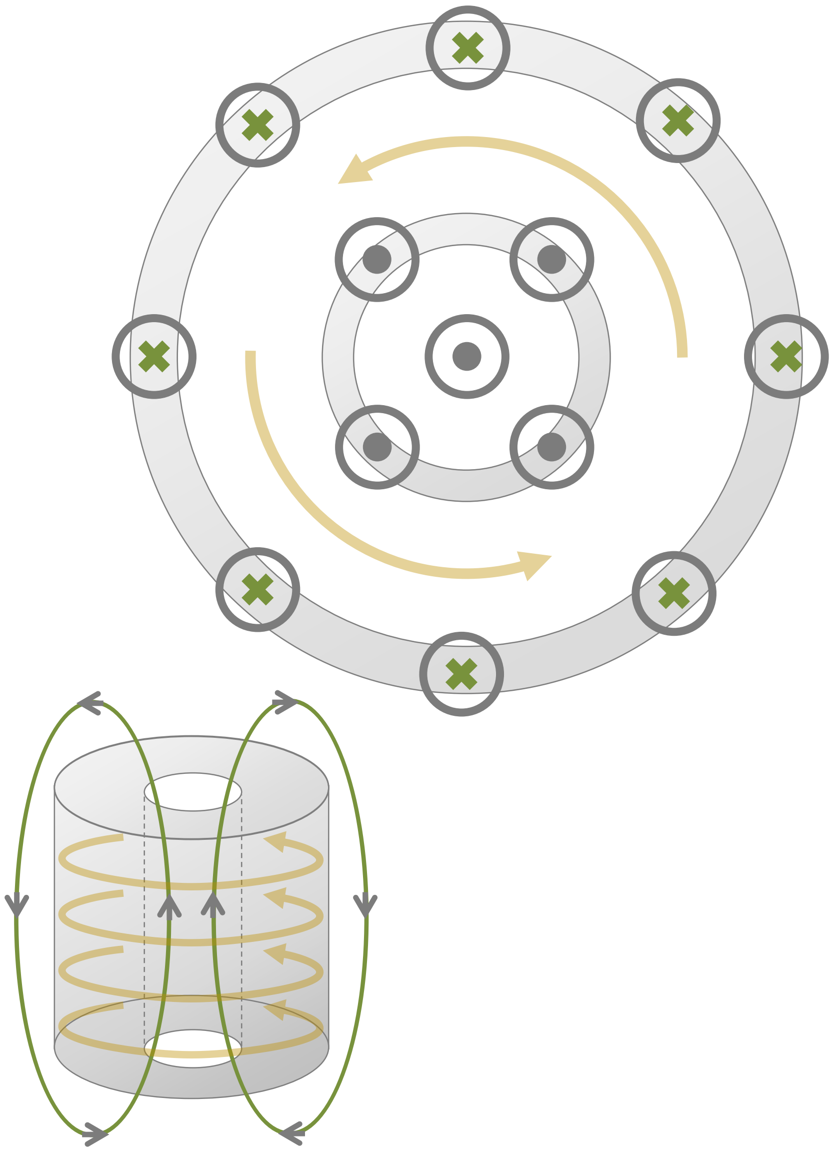

($B_0$ toroid *inside* cylinder)



- Toroidal coil produces DC magnetic field inside superconducting cylinder
- Axions interact with DC field, generates effective AC current along direction of applied field

$$\vec{J}_a = |\vec{J}_a|\,\hat{\phi}$$

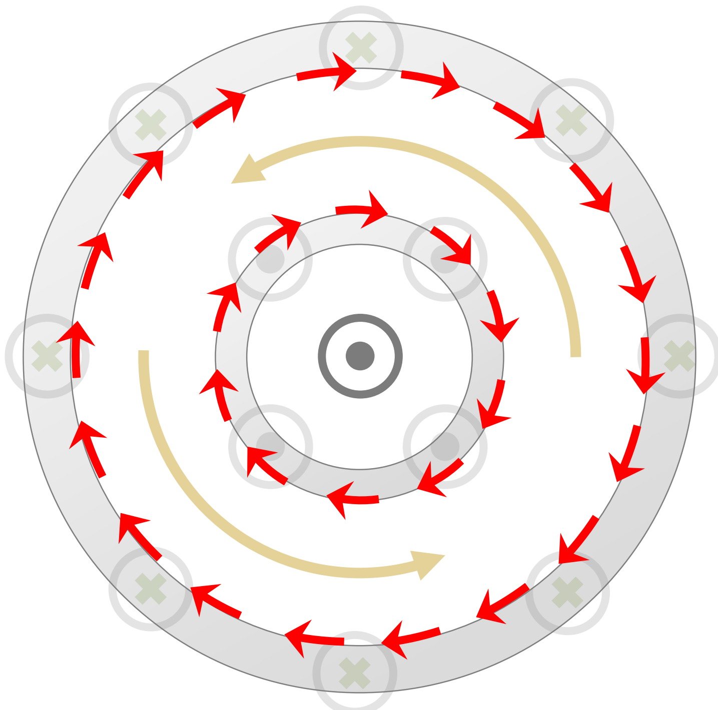
# How to measure effective axion current



- Toroidal coil produces DC magnetic field inside superconducting cylinder
- Axions interact with DC field, generates effective AC current along direction of applied field
- Produces REAL quasi-static AC magnetic field

$$\vec{B}_a(t)$$

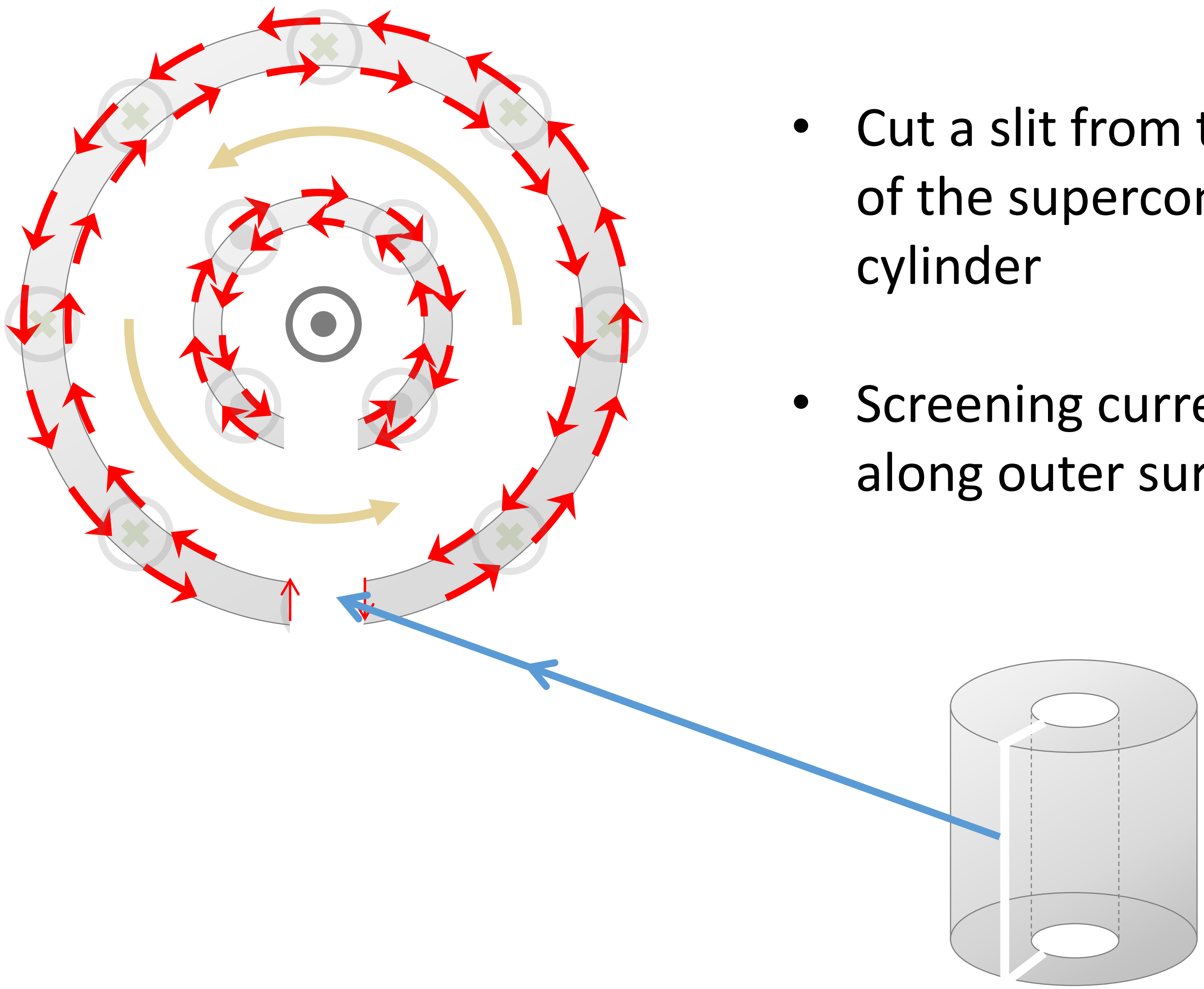
# How to measure effective axion current



Meissner Effect

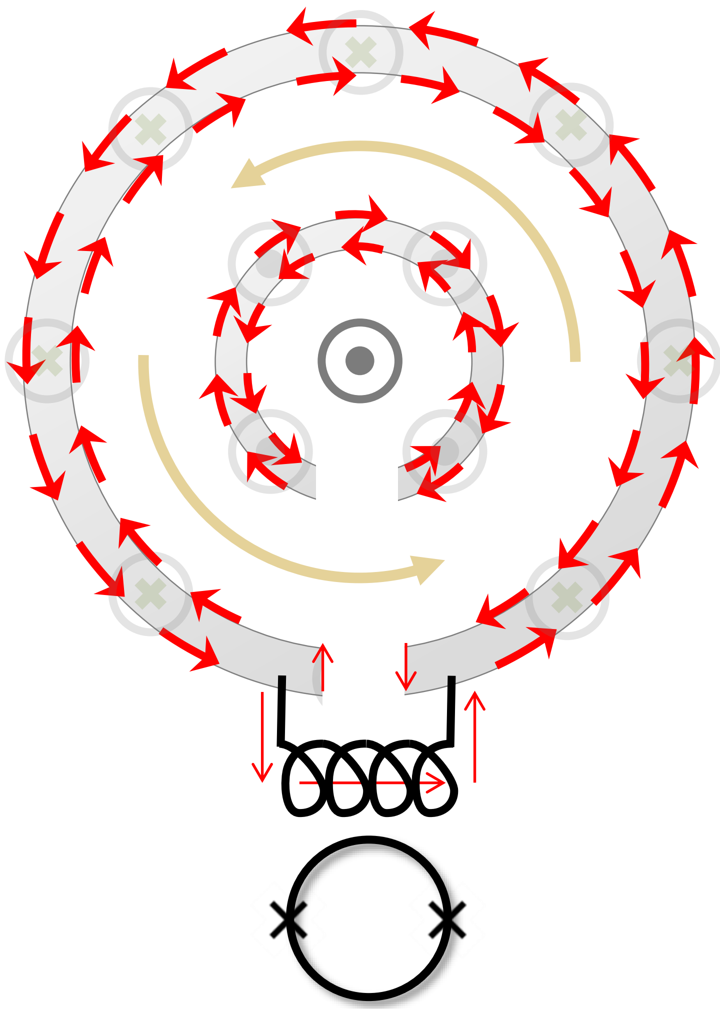
- Screening currents in superconductor flow to cancel field in bulk

# How to measure effective axion current



- Cut a slit from top to bottom of the superconducting cylinder
- Screening currents continue along outer surface

# How to measure effective axion current



- Cut a slit from top to bottom of the superconducting cylinder
- Screening currents continue along outer surface
- Use inductive loop to couple screening current to SQUID

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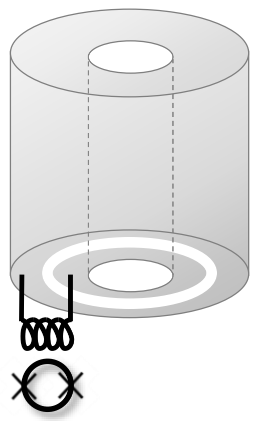
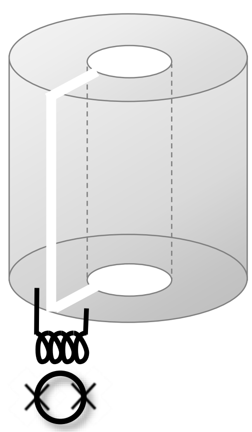
# Broadband detection: poor signal to noise

Hidden Photon Detector



Axion Detector



ABRACADABRA

Y. Kahn et al.

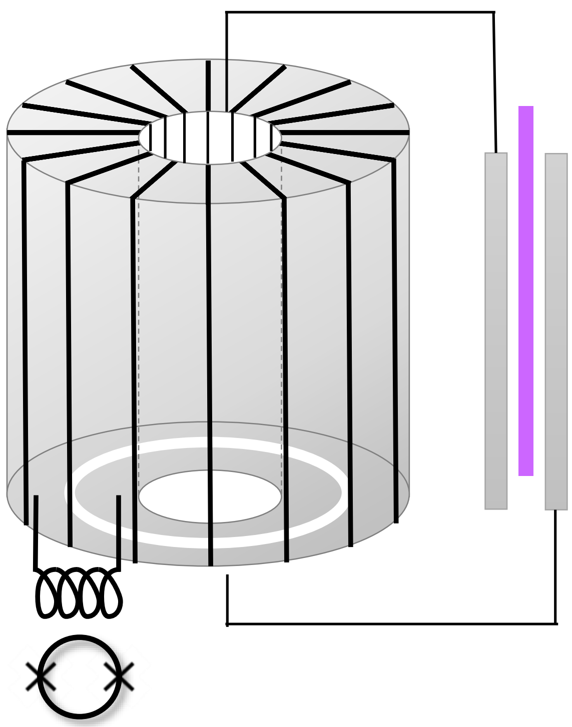
arXiv:1602.01086, 2016

- Broadband sensitivity
- Require long integration times for good sensitivity
- Interfering EMI pickup very difficult to manage

Poor signal-to-noise ratio

# Resonant enhancement

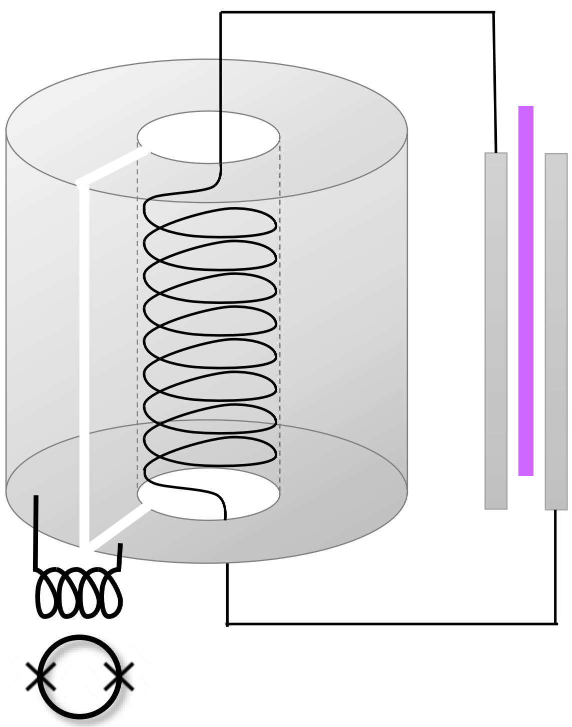
Hidden Photon Configuration



- Coherent fields can be enhanced through the use of a resonator
- Add a tunable lumped-element resonator to ring up the magnetic fields sourced by local dark matter
- Tune dark matter radio over frequency span to hunt for signal

# Resonant enhancement

<u>Axion Configuration</u>



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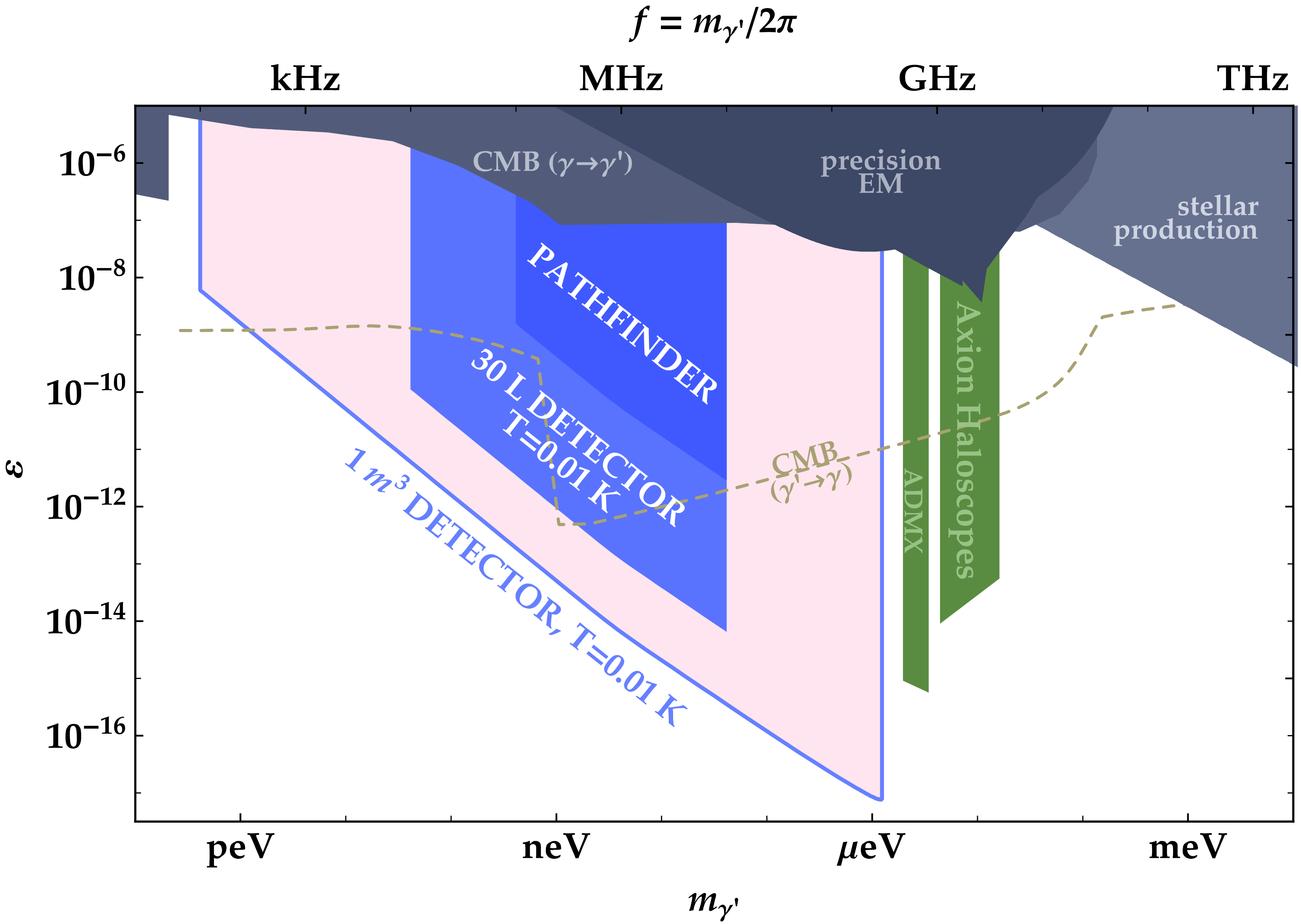
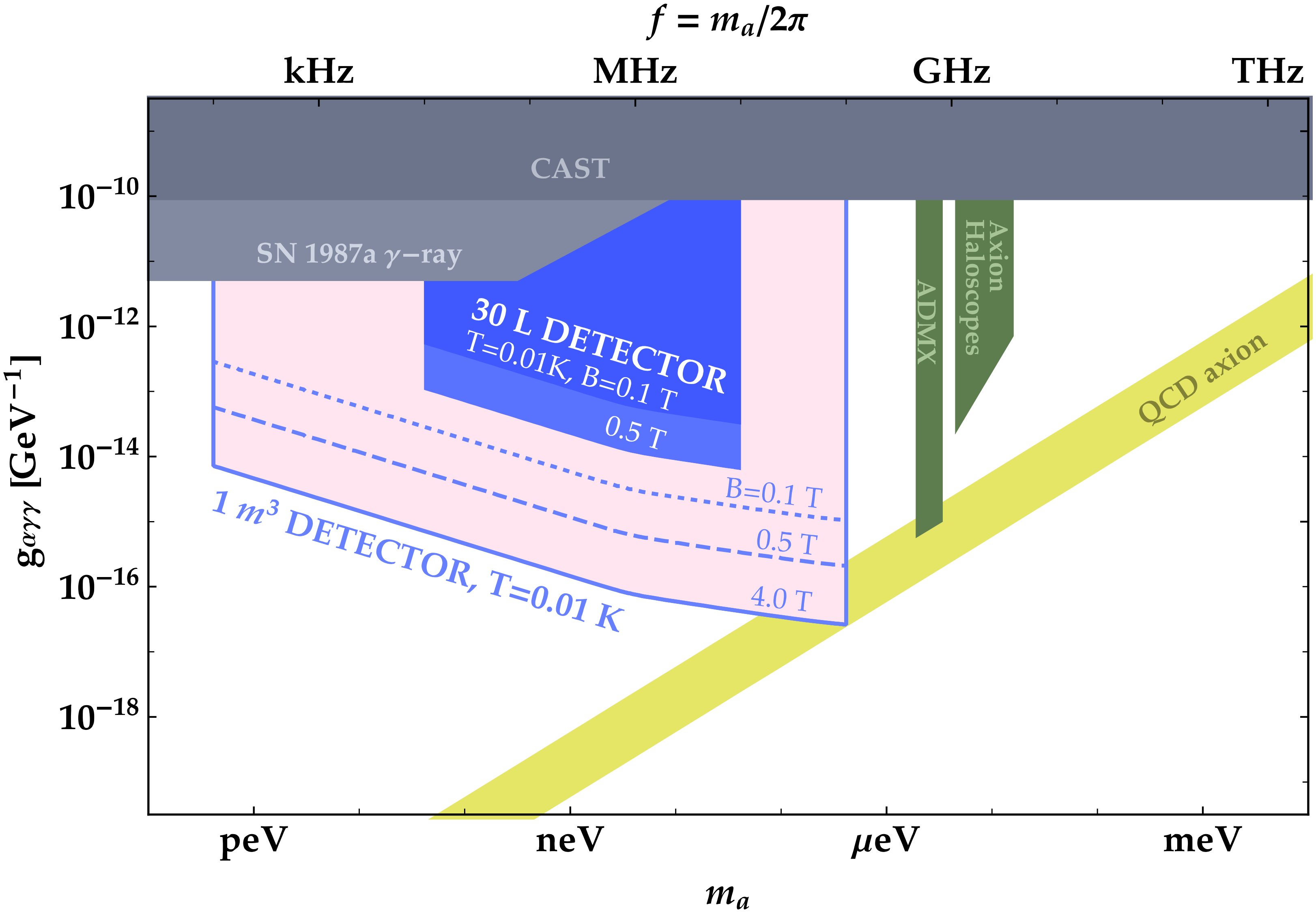
# DM Radio science reach: hidden photons (lumped-element)



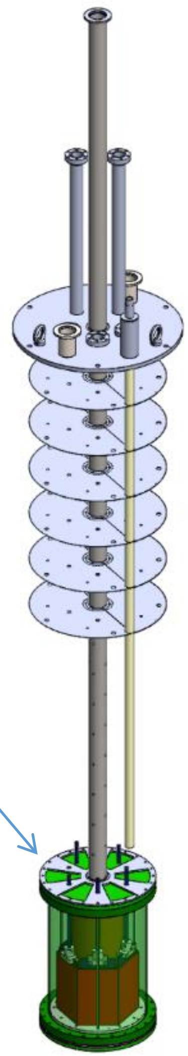
# DM Radio science reach: axions



# DM Radio pathfinder experiment

**4K Dip Probe**

Inserts into
Cryoperm-lined
helium dewar



Detector inside
superconducting
shield

9.5 inches

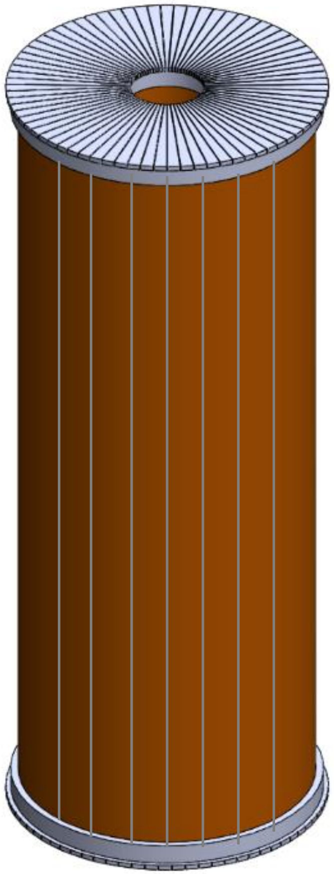
67 inches

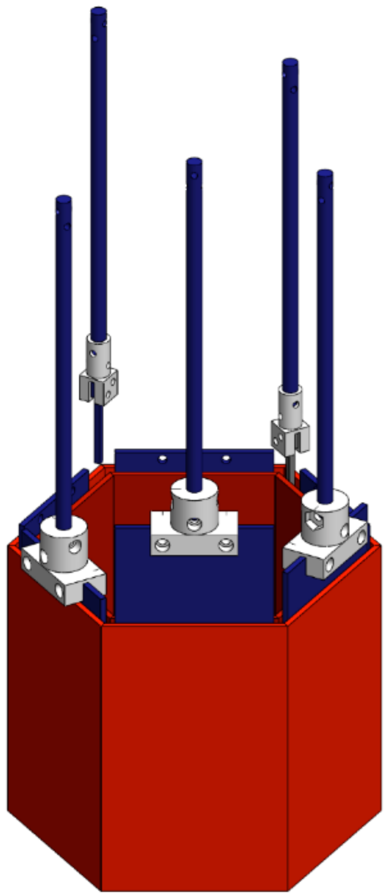
**750 mL Pathfinder funded, under construction**

- Focus on hidden photons
- T=4K (Helium Dip Probe)
- Frequency/Mass Range:
  100 kHz – 10 MHz
  500 peV – 50 neV
- Coupling Range
  $\varepsilon$ : $10^{-9} – 10^{-11}$
- Readout: DC SQUIDs

**Design Overview of the DM Radio Pathfinder Experiment**
M. Silva, arXiv:1610.09344, 2016

# Resonant frequency tuning





$$\frac{\Delta f}{f} \approx 1 \times 10^{-6}$$ per .001” of motion

**Scan time**

- 30 days/decade
- 3-6 months total

**Ultra-coarse tuning**

- fixed sapphire plate fully inserted/removed (tune C)
- change number of turns in solenoid coil (tune L)

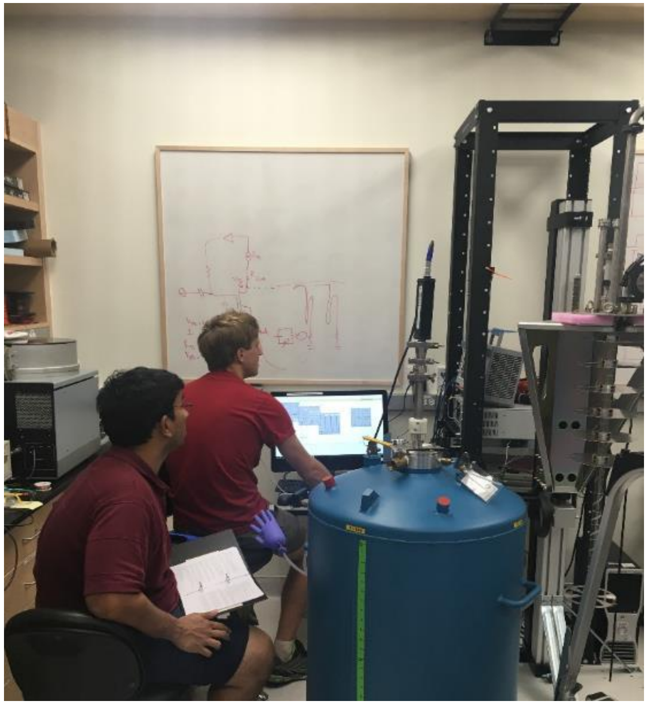
**Coarse tuning**

- position of sapphire dielectric plates (3)

**Fine tuning**

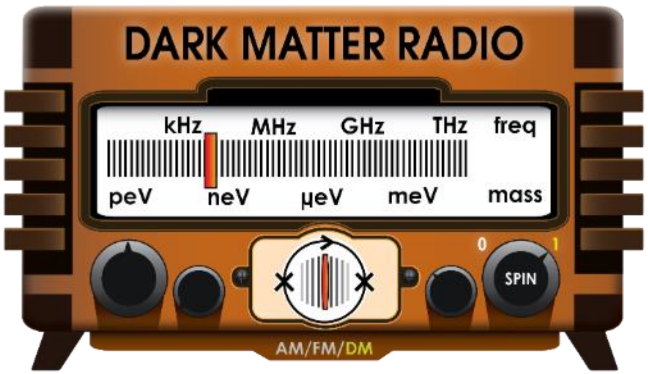
- position of sapphire needle
- position of niobium needle

# Present status - Pathfinder



- Probe construction complete
- Machining of niobium shield/SQUID annex complete, additional niobium parts being machined for scanning
- SQUIDs and readout electronics tested / working
- Now testing fixed resonators to evaluate Q, material properties, then scan
- **Initial science constraints Summer 2017**

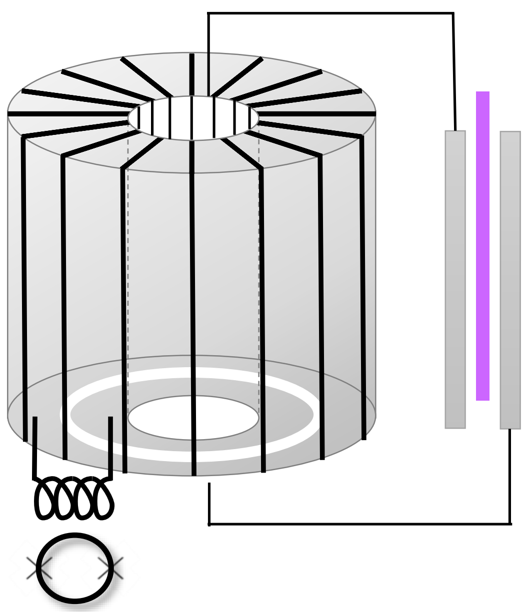
# Conclusions




**DM Radio:**

A Superconducting Lumped-Element
Dark Matter Detector
For Axions and Hidden Photons

Hidden Photons



Axions